PEDESTRIAN BLOCK FROM CERAMIC-BASED TILES WASTES: PROPERTIES, MODELLING AND OPTIMIZATION STUDIES

by

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LIST OF ABBREVIATIONS

Symbols	Description
A/C	Aggregate cement ratio
ACV	Aggregate crushing value
AIV	Aggregate impact value
ANN	Artificial neural network
AS	American Standard
BS	British Standard
CWC	Ceramic waste concrete
DOE	Department of Environment
GRNN	General regression neural network
HCP	Hardened cement paste
IBS	Industrialised Building System
ICP	Inductive Couples Plasma
IS	Indian Standard
ITZ	Interfacial transition zone
MAPE	Mean absolute percentage error
MLR	Multiple linear regression
MPPP	Penang Municipal Council
MPSP	Seberang Perai Municipal Council
MSSE	Mean sum squared error
MSW	Municipal solid waste
NaCl	Sodium chloride
NMA	Normal mixing approach
OLS	Ordinary least square

PET	Polyethylene terephthalate
PVC	Polyvinyl chloride
RA	Recycled aggregate
RAC	Recycled aggregate concrete
RBC	Recycled brick concrete
RCA	Recycled concrete aggregate
RCBA	Recycled concrete bricks aggregate
RGA	Recycled glass aggregate
RMS	Root-mean-squared
RPA	Recycled plastic aggregate
RPC	Recycled plastic concrete
RWCA	Recycled waste ceramic aggregates
SEDD	Scottish Executive Development Department
SEM	Scanning Electron Microscope
SSD	Saturated surface dried
SSE	Sum of square error
TSMA	Two-stage mixing approach
US EPA	United States Environment Protection Agency
W/C	Water cement ratio
XRD	X-ray diffraction
XRF	X-ray fluorescence

BLOK LALUAN AWAM DARIPADA SISA JUBIN BERASASKAN SERAMIK: KAJIAN SIFAT, PERMODELAN DAN PENGOPTIMUMAN

ABSTRAK

Pengurusan sisa buangan pepejal merupakan masalah yang besar dalam negara-negara membangun termasuk Malaysia. Dengan pembangunan luar bandar dan ekonomi yang pesat, pengurusan sisa buangan pepejal menjadi masalah kerana terdapat bahan buangan yang berlebihan. Biasanya, jubin seramik yang dibuang di tapak pembinaan akan dihantarkan ke tapak pelupusan untuk dilupuskan. Malahan, kekurangan bekalan agregat asli yang kritikal untuk penghasilan blok laluan awam serta lambakan jubin seramik yang banyak di tapak pembinaan telah juga menyebabkan masalah ekologi dan persekitaran yang teruk. Dengan itu, pemeliharaan alam sekitar dan pemuliharaan sumber asli yang kian merosot cepat adalah sifat utama pembangunan kelestarian.

Penyelidikan ini memberikan kaedah alternatif dalam penghasilan blok laluan awam dengan menggunakan sisa jubin seramik dari tapak pembinaan sebagai penggantian kepada agregat kasar (batu) dan halus (pasir sungai) asli. Kajian sifat-sifat kimia dan mineralogi telah dijalankan kerana ia akan mempengaruhi prestasi kekuatan konkrit. Dalam analisis pendarkilau sinar-X (XRF) dan belauan sinar-X (XRD), didapati blok laluan awam yang diperbuat daripada 100% agregat sisa jubin seramik mempunyai komposisi kimia SiO_2, CaO, Fe_2O_3 dan Al_2O_3 yang setanding dengan agregat asli. Kekuatan blok laluan awam agregat yang asli mempunyai

ketumpatan 2421.0 kg/m^3, manakala blok daripada agregat kasar dan halus jubin seramik adalah 2242.0 kg/m^3 dan 2381.0 kg/m^3, masing-masing. Kekuatan mampatannya pula adalah 50.5 MPa (asli), 49.5 MPa (kasar) dan 56.4 MPa (halus), manakala kekuatan lenturannya adalah pada 5.3 MPa (asli), 6.4 MPa (kasar) and 6.1 MPa (halus), masing-masing. Ketahanlasakan blok juga telah diuji secara mekanikal dan kimia. Keputusan menunjukkan blok laluan awam yang diperbuat daripada sisa jubin seramik agregat yang kasar tidak mempunyai proses pengkarbonan, dan ini akan memanjangkan masa hayatnya. Malahan, blok ini juga turut mempunyai rintangan yang tinggi terhadap tembusan klorida dan sulfat.

Dalam analisis pemindahan jisim, didapati satu interaksi kimia di antara agregat dengan simen wujud akan tetapi ianya akan berubah mengikut peratus penggantian dan jenis agregat (kasar atau halus) yang digunakan. Pekali kemeresapan bagi penggantian agregat kasar adalah lebih kecil daripada agregat halus.

Analisis regresi berbilang lelurus (MLR) telah dijalankan untuk menjana model pengoptimuman bagi mendapatkan kekuatan mampatan blok laluan awam pada 45.0 MPa. Keputusan simulasi menunjukkan padanan yang sesuai dengan data eksperimen yang diperolehi pada pelbagai peratus penggantian, dengan julat pekali regresi, r^2, dari 0.90 ke 0.99. Ini menunjukkan wujudnya perkaitan yang kuat di antara sifat-sifat bagi blok laluan awam. Untuk menghasilkan blok yang mempunyai kekuatan mampatan pada 45.0 MPa, sebanyak 75.5% agregat kasar atau 36.5% agregat halus sisa jubin seramik perlu digunakan. Malahan pula, agregat kasar and halus sisa jubin seramik boleh dicampurkan pada 65.4% dan 23.3% untuk mendapatkan kekuatan mampatan pada 45.0 MPa.

Satu sistem rangkaian neural buatan telah dijana untuk meramalkan ciri-ciri mekanikal blok laluan awam. Keputusan ramalan yang didapati mempunyai pecahan varians, R^2, dalam julat 0.90 ke 0.99 dan ini menjelaskan bahawa keputusan ramalan adalah berpadanan dengan data eksperimen. Ini menunjukkan bahawa penggantian jubin seramik adalah merupakan kaedah yang sesuai dan berkos rendah, lalu mengurangkan penggunaan sumber asli dan masalah persekitaran yang dihadapi oleh industri pembinaan.

PEDESTRIAN BLOCK FROM CERAMIC-BASED TILES WASTES: PROPERTIES, MODELLING AND OPTIMIZATION STUDIES

ABSTRACT

The management of solid waste materials is a problem in many developing countries including Malaysia. With an increase in urbanization and economic development, solid waste management has become an acute problem due to the emergence of more waste material. Ceramic tiles generated from construction sites were usually delivered to landfills for disposal. A critical shortage of natural aggregates for the production of new pedestrian blocks also occurred, and an enormous amount of ceramic tiles produced from deteriorated and construction sites created severe ecological and environmental problems. Preservation of the environment and conservation of the rapidly diminishing natural resources should be the essence of sustainable development.

This research addressed an alternative method in producing pedestrian block using ceramic tile waste materials from construction sites as a substitute of natural coarse (rocks) and fine (river sand) aggregates. The chemical and mineralogical characterizations were carried out as it would influence the concrete performance. The X-ray fluorescence (XRF) and X-ray diffraction (XRD) patterns showed that pedestrian blocks from 100% recycled aggregates of ceramic tiles and natural aggregates had a comparable chemical composition of SiO_2, CaO, Fe_2O_3 and Al_2O_3. The pedestrian block performances were at unit weight 2421.0 kg/m^3 using natural

aggregates, and 2242.0 kg/m^3 and 2381.0 kg/m^3 from ceramic tiles coarse and fine aggregates, respectively. The compressive strength were at 50.5 MPa (natural), 49.5 MPa (coarse) and 56.4 MPa (fine), while the flexural strength was at 5.3 MPa (natural), 6.4 MPa (coarse) and 6.1 MPa (fine), accordingly. The durability of the blocks were also tested mechanically and chemically. Results showed that pedestrian blocks from ceramic tile waste coarse aggregates do not have any carbonation process, thus prolonging their life cycle. In fact, the blocks were found to be highly resistant to chloride and sulphate penetration.

For the mass transfer analysis, a significant aggregates-cement chemical interactions occurred but varied according to the percentage of replacement and the type of aggregates (fine or coarse) used. The coefficients of diffusivity for coarse aggregates were smaller compared to the fine aggregates replacement.

A multiple linear regression (MLR) analysis was carried out to generate models for the optimization of pedestrian block with a compressive strength of 45.0 MPa. The results of the model simulation showed very good agreement with the experimental data obtained at varying percentage of replacement, with the regression coefficient, r^2, ranging from 0.90 to 0.99, indicating that a strong correlation occurred among the properties of the pedestrian block. In order to produce blocks with a compressive strength of 45.0 MPa, the coarse and fine ceramic tile-based aggregates were used at 75.5% and 36.5% replacement to obtain a similar strength. In fact, tile-based coarse and fine aggregates could be combined at 65.4% and 23.3% to obtain compressive strength of 45.0 MPa, consecutively.

An artificial neural network system was built for the prediction of pedestrian block mechanical properties. Results showed that the predicted results had an absolute fraction of variance, R^2, within the range of 0.90 to 0.99, thus indicating that the predicted results were close to the experimental data. This showed that replacement of ceramic tiles were feasible and of low cost, hence, reducing the consumption of natural resources and environmental problems faced by the construction industry.

CHAPTER ONE

INTRODUCTION

1.1 Overview

With an increase in population, the upsurge of urbanization and rising standards of living due to technological innovations, have contributed to an increase in both the quantity and variety of solid wastes generated by industrial, mining, domestic, agricultural, and construction activities (Pappu *et al.*, 2007). It was reported that the estimated quantity of solid waste generation was 12 billion tonnes in the year 2002, of which 11 billion tonnes were municipal solid wastes (MSW) and expected to rise till 19 billion tonnes of solid wastes by the year 2025 (Yoshizawa *et al.*, 2004). Asia alone generated about 4.4 billion tonnes of solid wastes a year (Pappu *et al.*, 2007).

Traditionally materials like clay, sand, stone, gravel, cement, brick, block, ceramic tiles, distemper, paint, timber and steel were used as major building components in the construction sector (Pappu *et al.*, 2007). However, solid wastes produced from the construction sector were becoming serious environmental problem in many large cities in the world. These solid wastes were usually from construction, remodeling and repairing of individual residences, commercial buildings, and other civil engineering structures (Figure 1.1) (Huang *et al.*, 2002; Oikonomou, 2005).

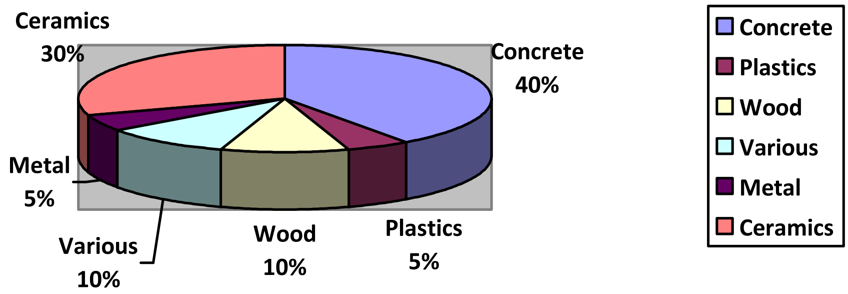

Figure 1.1 Approximate basic composition of solid waste by the construction sector (Oikonomou, 2005)

Begum *et al.* (2006) reported that construction waste debris frequently made up 10 – 30% of the wastes received at many landfills sites all over the world. The United States Environment Protection Agency (US EPA) estimated 136 million tonnes of building-related construction debris generated in the United States in 1996. This represented about one-third of the volume of materials in landfills. Canada landfills used about 35% of its space for construction wastes and debris (Esin and Cosgun, 2007). Rao *et al*. (2007) estimated that the annual generation of construction and demolition waste in the European Union could be as much as 450 million tonnes, which was one of the largest single waste streams, apart from farm wastes. Even if earth wastes were excluded, the construction wastes generated were estimated to be 180 million tonnes per year. With an estimated population of 370 million, the per capita annual wastes generation was about 480 kg. In Scotland, the Scottish Executive Development Department (SEDD) estimated that the quantity of land filled at all sites were approximately 4173 kilotonnes, of which 44% were mixed construction wastes, clean soil (34%), contaminated soil (13%) and contaminated construction wastes and asphalt (9%) (Rao *et al.*, 2007). The United Kingdom generated about 20 million tonnes per annum of construction wastes. The bulk of them came from concrete (50-55%) and masonry (30-40%) with only small percentages of other materials such as metals, glass and timber (Tam and Tam, 2007). In Australia, about 32.4 million tonnes of solid wastes were generated annually of which about 42 % was from the construction sectors (Tam, 2009).

East Asian countries have their fair share of construction and demolition wastes. Hong Kong with a population of about 6.8 million had scarcity of land. In 2004, a total of 20 million tonnes of construction wastes were generated (Poon and Chan, 2007). In Taiwan, construction wastes frequently constituted between 15 and 20% of municipal solid wastes (MSW). Currently, a total of 75 million tonnes/year (about 19% of total industrial waste) of construction and demolition wastes were generated in Japan (Kawano, 2003). Thailand generated 1.1 million tonnes of construction wastes per year. This report was based on the basis of Thailand's population from 2002 – 2005 using the construction activity time-series data for the same period. Approximately 12 kg of construction wastes were generated per person in 2002; this amount had risen to approximately 18 kg in 2003 and 22 kg in 2004, with a slight decreased to about 20 kg/cap in 2005. This implied an average rate of construction waste generation of about 18 kg/cap/year for Thailand within this period (Kofoworola and Gheewala, 2009). However, there are very few published data on the amount of construction wastes generated in Malaysia. In fact, its utilization to value-added materials is scare.

1.1.1 Construction waste generated by natural disasters

In 1999, a severe earthquake in Central Taiwan caused severe structural damage to about 100,000 dwellings. It was predicted that an additional several million tonnes of construction wastes were going to be generated during structural rebuilding and repair in the future (Huang *et al.*, 2002). 26th December 2004 was a grave and sad day as a tsunami swept through Sri Lanka, Indonesia, Malaysia and Thailand. The loss and devastation caused by this disaster brought incalculable suffering to millions of people around the Indian Ocean.

Although the earthquake shaking caused significant damage, the large majority of building damage was caused by the tsunami waves (Fehr *et al.*, 2006). In Sri Lanka, the most common housing construction type is unreinforced masonry, which is particularly vulnerable to collapse from the tsunami waves. The devastation has been much more in Sainthamaruthu, Kalmunai and Maruthamunai of the densely populated towns in the southeastern coast (UNEP, 2005). About well over 0.5 million tonnes of rubble and waste materials were found in Sri Lanka (Basnayake *et al.*, 2005). Most of the wastes were generated from destroyed masonry houses within 20 to 30 m of the shoreline. These houses were mostly consisted of reinforced concrete frames with infill masonry and was estimated that about US$1,000 million was loss during the tragedy (Fehr *et al.*, 2006). The quantity of woody materials and construction debris were posed as considerable problems to the habitants and local authorities in this country. Not only that, large quantities of broken-up asbestos roofing sheets are a common site and posed to be a serious hazardous pollution (Selvendran and Mulvey, 2005). However, in a lot of the affected areas, foundations of most buildings still remain. Some house owners reuse this construction debris to get bricks and cement blocks for reconstruction purposes.

During the tsunami, Thailand had three major categories of solid wastes identified in the affected area according to their disposal requirements. They are municipal solid waste generated by the people living in the area, infectious waste from dead human/animal bodies and medical activities and the debris from demolished construction works which totaled about 76,250 tonnes on-land area and 252 tonnes from the sea. Most of the demolition wastes were mainly consisted of building debris (concrete, brick), wood materials, metals and mud with sand (Basnayake *et al.*, 2005). Traditional Thai architectures used wood framing and bamboo for construction, resulting in a lightweight frame with light openings. Many timber frame structures from the beach resort areas. Other hotels on the beach area are mid-rise reinforced concrete of superior construction standards. These buildings typically have shear walls in the transverse direction, larger columns, and other walls formed by cast-in-situ (cast in place rather than prefabricated) unreinforced masonry panels. Some of these structures performed remarkably well, even in locations where the tsunami reached or even exceeded (Fehr *et al.*, 2006). All in all, Thailand had a loss of US$ 1,000 million in property and building damages. A lot of these wastes were managed in few different ways depending on the local authorities. Some municipalities like Pathong Municipality in Phuket province and PP island in Krabi province hired private sector to dispose the wastes in private lands. In some other areas, the recyclable materials were separated and reclaimed by scavengers before the disposal of the remaining wastes by responsible local authorities. However, not all local authorities have got such support for managing their wastes. Some municipalities or sub-district administrative organization lacking financial resources and external support, are still suffering from the accumulation of those wastes. Until now, some amount of demolition wastes were still left over on roadsides (Basnayake *et al.*, 2005). Most recycling practices in Thailand were done by the informal sector. The scavengers usually spate and pick up valuable materials in the wastes and sell them at junk shops. Unfortunately, recycling of construction and demolition wastes is not widely practiced in Thailand. This was due to the lack of heavy crushing machine to reduce the size of waste materials, which make it easily recyclable (WminE, 2005).

A rough order calculation for the city of Banda Aceh, Indonesia alone estimates the volume of waste at between 7 and 10 million cubic metres. The effect of the tsunami was variable. In some parts of the west coast, most debris was swept out to sea. The composition of the waste material in former population centres is also varied. There are high volumes of mud and sand in Banda Aceh (less so in Meulaboh) and nothing visible is left in Calang. The other main constituents are, in rough order of volume: bricks ad concrete; wood (planks and trees and other organic matter); some plastics and metals (iron, aluminium and copper). Overall, an estimated 80% of the waste being collected consists of soil, building materials or vegetative matter (UNEP, 2005). About 60%-70% of the waste was generated from residential sources, and the remaining from non-residential sources (Fehr *et al.*, 2006). Each house generated about 50 to 64 tonnes of brick and concrete wastes where most of them were in temporary dumpsites in Banda Aceh and Gampung Jawa. More than 85% of all metals such as copper, aluminium, iron and steel were collected by informal scrap dealers from the sites itself or from temporary dumpsites and landfill site to be sold on the market (mostly in nearby city of Medan). This included iron rods used in reinforced concrete buildings. Traditional wooden houses would have generated debris to the about 10 – 15 kg/m^3 and modern brick and concrete houses of 20 – 25 kg/m^3 (DEBRI, 2008).

The tsunami that hit Malaysia targeted the states of Penang, Kedah, Perak and Selangor (Siwar, 2005). Despite its proximity to the epicenter of the earthquake, Malaysia escaped the full devastating damage that struck other countries thousands of miles away, being shielded by the island of Sumatra. Although the earthquake resulted in minor tremors in Penang and other parts of the country it was three hours later than the northern coastal areas. In comparison to Sri Lanka, Thailand and Indonesia, the impact of the tsunami was minimal. Nevertheless, some structural damage was done to residential areas nearer to the coast (POHD, 2005). Malaysia was recorded to have about 398 structural damages and about 1000 tonnes of wastes were generated (Siwar, 2005). These homes were found along the beaches and mostly belonged to fishermen (POHD, 2005). The wastes collected were sought and materials like wood and concrete were recycled to build and repair homes not as badly damaged by the tsunami (Siwar, 2005).

Following the disaster, quite a number of proposals for the establishment of a regional early warning system were developed. In addition to such a regional system, much attention should also be given to enhancing the capabilities of the coastal population in foreseeing the occurrence of natural disasters and preparing for them. Knowledge acquired by traditional communities, from observations and from scientific research on the tsunami and other natural disasters should be used to educate vulnerable coastal communities, in particular through school curricula.

1.1.2 Construction wastes management systems in Malaysia

Managing of construction solid wastes is achieved by preventing and minimizing the generation of wastes, as well as managing those wastes in such a manner that they do not cause harm to health, and the environment (Pereira, 2003). Among the various waste management methodologies were (Begum *et al.*, 2007): (a) reducing the wastes, (b) reusing the wastes, (c) recycling the wastes, and (d) disposing the wastes. It was reported that the environmental benefits of wastes minimization include prolonging the life of landfill sites, and reducing the primary resource requirements (CIRIA, 1993). Lingard *et al.* (2000) stated that the social benefits included the avoidance of creating new and undesirable landfill sites, stemming potential environmental health risks associated with wastes and cost reduction for disposal.

Such wastes could be reduced by minimizing its generation during the construction's operational processes. In fact, its reduction could also be maximised by reducing the material in-flow, and thus reducing the materials out-flow (Pereira, 2003). Extra construction materials were usually planned due to lack of consideration given to wastes reduction during the planning and designing stage so as to minimize the generation of these waste (Begum *et al.*, 2007).

According to Buhe *et al.* (1997) reuse of wastes is considered as a closed-loop recycling, where a product of a system is recycled for a new use in the system. Many construction materials could be reemployed after refurbishment for a lower-grade application. For example, excavated soil could be used as backfill, for landscaping or noise building (Pereira, 2003).

Recycling is another important factor in solid wastes management systems. Recycling is actually an open-loop process where waste products of a system find new use in another system (Buhe *et al.*, 1997). An example would be the recycling of concrete where the concrete is crushed to produce secondary aggregates, while used metals could be moulded into new products (Pereira, 2003). The economic and environmental benefits to be gained from waste recycling are enormous. Recycling offered these benefits such as (Tam and Tam, 2006; Kofoworola and Gheewala, 2009):

(i) reduced the demand upon new resources

(ii) cut down on transportation and production energy costs

(iii) used wastes which would otherwise lost to landfill sites, thus prolonging their life, and

(iv) created potential job vacancy

In construction industries, recycling of solid wastes was a very common practice in many developed countries like the United States, Canada, Europe, Australia and also a few East Asian countries (Huang *et al.*, 2002; Tam and Tam, 2006). Table 1.1 showed the recovery rates of several types of materials, such as paper, plastic, metals, and glass in some of the countries.

Table 1.1 Recovery rates of common recyclable materials (Tam and Tam, 2006)

Place	Year	Paper (%)	Plastic (%)	Metals (%)	Glass (%)
Hong Kong	2001	58	38	89	3
Australia	1995	51	72	88	42
Japan	2000	58	14	75	78
USA	1999	42	6	35	23
Germany	1999	169[a]	108	192	88
United Kingdom	1998	38	3	78	22

[a]Percentages greater than 100% means materials being recycled for more than one time

Unfortunately, the non availability of detailed characteristics and estimates of wastes from the construction sector in Malaysia has hindered economic evaluations and development of waste industries in the country. Recycling of solid wastes were important economic activities where many groups were interested but afraid to venture into the business due to lack of adequate data regarding its feasibility (Pereira, 2003). In addition to that, very few contractors have spent efforts in considering the environment and developing the concept of recycling building materials because they rank timing as their top priority, where completing the project in the shortest time possible is more important than the environment. Recycling materials required an aggressive marketing effort to locate markets and sell materials at the highest possible prices. Thus more time and money must be invested in establishing both the relationships, keeping track of pricing changes, and becoming a reliable supply of materials (Begum *et al.*, 2006). In addition, Malaysia also does not have a database and mechanism to disseminate information on building materials of locally available natural resources through collaborative efforts between private and public sectors. There are also very few promotion of research, training, information exchange and technology regarding waste management in the construction industry to establish and strengthen institution in this area (Pereira, 2003).

1.1.3 Solid wastes disposal system

At present, the disposal of solid wastes was mainly done by dumping. In the year 2003, there were about 168 dumping sites left and 7 of this total were sanitary landfills. The remainder sites were open dumps and 80% of these dumps would have filled up to the brim and closed by 2005 (Sangaralingam, 2003). In 2004, it was recorded that about 43% of the existing landfills and dumpsites would exceed their capacity within the next 5 years in Peninsular Malaysia (MEWC, 2004). The Penang Municipal Council (MPPP) estimated that in 2007, about 594 tonnes/day of solid waste were sent to the landfill owned by the council (MPPP, 2009). While the Seberang Perai Municipal Council (MPSP) estimated about 700 metric tonnes/day of solid wastes were sent to one of the 3 landfills managed by them (MEWC, 2004).

As reported by a few researches, about 30% of solid wastes generated by the construction industry came from ceramic wastes such as tiles, sanitary installations and bricks (Oikonomou, 2005; Rojas *et al.*, 2006). It was estimated that about 3.1% to 4.8% of ceramic tile wastes were generated for each construction project where a significant amount of wastes which will finally be disposed off in landfills (Yuliani, 2007). Generally, ceramic tiles were usually used as a finishing in any construction activity and were no strangers to the trend witnessed in recent years in numerous products of the so-called traditional industrial sectors (Berto, 2007; Yuliani, 2007). However, ceramic tiles did not enjoy great technological aureole, and the high profile of being a product of the future. Thus, many waste ceramic tiles were just thrown and land filled (Berto, 2007; Bogo, 2009).

Pereira (2003) reported that many of the construction solid wastes were discarded as they did not meet the specifications or had either become damaged or contaminated. Besides that, construction wastes could also be generated due to the presence of excessive construction materials at the construction sites. Another main environmental concern was the existence of various hazardous substances in the solid wastes generated by the construction sector, for example, asbestos, which was hazardous by itself and polyvinyl chloride (PVC), which in some treatment techniques caused emissions of toxic gases (dioxin) (Fatta *et al.*, 2004). As a result, many developers now turn to other means of disposing waste materials such as open burning which consequently caused air pollution. In fact, they seemed to have low awareness of the need for waste reduction, and were really no bothered about waste management. In other words, the tendency to cause excessive wastage of raw material rose tremendously.

1.1.4 Construction wastes generation in Malaysia

In Malaysia, the average amount of municipal solid wastes generated was approximately 1.2 kg/day in 2000 (Agamuthu, 2001; Begum *et al.*, 2009). This figure had risen tremendously by the year 2004, where an estimated 23,263 tonnes/day of solid wastes were generated (MEWC, 2004). The quantities of the municipal solid wastes varied among the local authorities in Malaysia depending on the township size and level of economic standards. The amount generated may range from 45 tonnes/day of municipal solid waste (MSW) in Kluang which is a small town in the southern part of Peninsular Malaysia, to 3000 tonnes/day in Kuala Lumpur (Agamutu *et al.*, 2004; Begum *et al.*, 2009).

However, there is no comprehensive data on the amount of solid wastes produced by the construction sectors in Malaysia. Hassan *et al.* (1998) reported that the breakdown of wastes generation according to sources were 36.73% from household wastes, 28.34% from industrial and construction wastes while other sources (market and commercial wastes, institutional wastes, landscaping wastes and street sweeping wastes) accounted for the remaining 34.93%. As of July 2008, the population of Malaysia has rose up to about 25.27 million people (CIA, 2008). These estimates were bound to increase steadily as the number of population in Malaysia increases.

1.2 Problem Statement

The construction industry had recorded an impressive growth of 6.4% compared to the overall GDP growth of 6.7% per annum for the economy during the period of 1971-1990. This value is expected to grow at 6.6% per annum during the period of 2001-2010. The statistics of the construction industries for the year 2003 showed that the value of construction works were RM 39.87 billions, and out of this value the cement and concrete materials alone cost RM 5.35 billions. The demand for the construction industry was high and it appeared likely that more concrete will be needed (Kamaruddin, 2003).

However, the usage of concrete is higher indicating that more raw materials - e.g. aggregates for the production of cement and concrete; will be needed, thus reducing the availability of natural resources. However, a major impact that associates with the depletion of natural resources is the modification of river profiles and their equilibrium due to extensive extraction and quarrying, hence inducing environmental problems such as modification of hydrological and hydro geological framework of the stated area. On the other hand, quarrying from mountainous areas (countries like Malaysia) would also alter the landscape, and potentially trigger stability problems and also cause problem for the level and quality of groundwater (Fatta *et al.*, 2004; Bianchini *et al.*, 2005). With these looming problems, the Industrialised Building System (IBS) looks at an alternative method for solid waste management for the construction industry (Yuliani, 2007; Begum *et al*., 2009). As reported by Kamar and Hamid (2009), the IBS has been touted as an efficient solution to project demand in the future while increasing efficiency, and reducing waste compared to the conventional method in construction. By taking a holistic view of recycling approach, non-renewable material consumption can be optimized and wastage can be reduced, gearing the concept of zero waste in the construction industry (Kamar and Hamid, 2009). In fact, the Malaysian government strongly support the usage of IBS for the construction sector due to its quality assurance, shorter construction period, cleaner site condition, safer working environment, and reduction and management of solid wastes generated by this sector. On the whole, the advantage of the IBS is focused on the minimization of solid wastes dumped into landfills which are quickly filling up to the brim (Yuliani, 2007).

At present, there are a lot of researches on recycling ‘wastes’ concrete to become an alternative aggregates in the construction industries. Such recycled aggregates could be a reliable aggregate as compared to natural aggregates in the concrete construction (Rao *et al.*, 2007). In recent years, crushed clay bricks and waste glass were used as alternative aggregates in concrete production (Poon and

Chan, 2006; Poon and Chan, 2007). However, in the ceramic industry about 30% of the production had gone to wastes, which were not recycled (Senthamarai and Manoharan, 2005). Most of these ceramic wastes are thrown and buried in the landfills. As reported by Senthamarai and Manoharan (2005), ceramic based wastes are not fully tapped as an inorganic industrial residual product in making concrete. Ceramic is durable, hard and highly resistant to biological, chemical and physical degradation forces. Therefore, it is important to explore the need to recycle such ceramic aggregates and understand the chemical-mineralogical and physical properties of these alternative aggregates. This is to build suitable on-site sorting and providing data that should be considered in order to develop correct recycling strategies (Bianchini *et al.*, 2005). Thus leading to sustainable concrete design and greener environment.

1.3 Research objectives

The main objectives of this study are to manufacture concrete pedestrian block from ceramic-based tiles construction wastes, as a replacement to natural aggregates. The measurable objectives of this project are as follows:

1. To investigate the chemical and physical properties of homogeneous ceramic tiles-based wastes.

2. To test and investigate the properties of manufactured pedestrian block.

3. To propose a model that relates to the mechanical properties of manufactured pedestrian block using multiple linear regression (MLR) analysis.

4. To develop an optimum mix proportion for the manufacturing of pedestrian block.

5. To generate an algorithm for mechanical properties prediction of the manufactured pedestrian block.

6. To compare the cost of the manufactured pedestrian blocks and also the market price of conventional pedestrian blocks.

1.4 Thesis organization

There are five chapters in this thesis and each chapter described the sequence of this research.

Chapter One presents the issue of generation of construction wastes either globally or locally. This is followed by the management and disposal system of construction wastes found in Malaysia. This chapter also presents the problem statement, research objective, scope of research and thesis organization.

Chapter Two covers an overview of related knowledge on construction wastes utilization. In addition, this chapter also gives a brief explanation on the materials to produce the pedestrian block. It is followed by the physical and chemical properties of the pedestrian block and its' uses. Next, this chapter also discussed the manufacturing of pedestrian block using alternative aggregates from construction wastes. The physical, chemical and mineralogical properties of ceramic materials were described in detail with the description of its types and usages. Moreover, the history on the usage of waste ceramic aggregates was given in this chapter as well. The cementitious properties of the pedestrian block were also discussed. This is followed by the modelling and optimization of the pedestrian block mechanical properties. Finally, the review touched on the usage of artificial neural network on process prediction as employed in this experimental work.

Chapter Three refers to the materials and methods describing the experimental procedures for recycling ceramic-based tiles wastes aggregate to manufacturing pedestrian block. This chapter also covers the chemical, mineralogical characterization of such wastes prior to and post manufacturing of pedestrian blocks. In fact, the physical and morphological characterizations of the manufactured pedestrian blocks were discussed in detail. Multiple linear regression (MLR) analysis methods were used to optimize the mix proportion while artificial neural networks were used for the prediction purposes.

Chapter Four presents the experimental results and discussions. It is divided into several parts based on the chronology of the work to provide an ideal flow of information, and subsequently an easier understanding to the study. The first section is the physical and chemical properties of the homogeneous ceramic tiles, and comparing it to natural aggregates. Next is the analysis of the workability and compacting factor of the pedestrian block made with both natural and recycled aggregates. This is followed with the mass transfer studies and optimization of strength using MLR analysis. Consequently, prediction of mechanical properties of pedestrian block is explained using neural-network.

Chapter Five concludes on the findings of these studies and the recommendations for the improvements, which can be done for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Pedestrian block

Pedestrian blocks are very common in many urban areas. In the Kyoto protocol, urban areas are now becoming the cornerstone in the implementation of strategies for resource conservation and efficiency on its use, establishing an intrinsic union between the concepts “cities” and “sustainability” (Harper and Graedel, 2004). Thus, the pedestrian block is usually viewed as an environmentally and economically sustainable choice, primarily due to its durability and low maintenance requirements (Atici and Ersoy, 2008; ACPA, 2007). High durability ensures that the desirable performance characteristics and environment advantages of concrete paving remain essentially intact for several decades (Oliver-Solà *et al.*, 2009).

2.1.1 Materials to produce pedestrian block

The main stages of producing the pedestrian block are as follows: raw material extraction, material processing, soil compaction, pedestrian block installation, maintenance and materials transportation (Oliver-Solà *et al.*, 2009). Pedestrian block are mainly made with concrete. Concrete is composed mainly of three materials, namely, cement, water and aggregates (Dhir and Jackson, 1996). Concrete is a man-made composite and remains an important building material. World-wide, more than 10 billion tonnes of concrete and pedestrian blocks are produced each year (Meyer, 2009). The reasons for this popularity are well known as it is usually used structurally in buildings for foundations, columns, beams and slabs, in shell structures, bridges, sewage-treatment works, railway sleepers, roads, cooling towers, dams, chimneys, harbours, off-shore structures, coastal protection works and others. In fact, it is also used for a wide range of precast concrete products including concrete blocks, cladding panels, pipes and lamp standards. In addition to its potential from aesthetic considerations, concrete required little maintenance and had good fire resistance.

2.1.1 (a) Cement

Cement is finely ground powder and has important properties that when mixed with water a chemical reaction (hydration) took place, thus producing a strong binding medium for the aggregate particles. It is during the early stages of hydration, while in its plastic stage, cement gives to the fresh concrete its cohesive properties. Of the many different cement manufactured, the most widely used (also in this research) is Ordinary Portland cement. Portland cement consists of 5 major compounds as listed in Table 2.1.

Table 2.1 Composition of portland cement with chemical composition and weight percent (MAST, 2003)

Cement Compound	Weight (%)	Chemical Formula
Tricalcium silicate	50%	Ca_3SiO_5 or $3CaO.SiO_2$
Dicalcium Silicate	25%	Ca_2SiO_4 or $2CaO.SiO_2$
Tricalcium aluminate	10%	$Ca_3Al_2O_6$ or $3CaO.Al_2O_3$
Tetracalcium aluminoferrite	10%	$Ca_4Al_2Fe_2O_{10}$ or $4CaO.Al_2O_3.\ Fe_2O_3$
Gypsum	5%	$CaSO_4.2H_2O$

2.1.1 (b) Aggregates

Aggregates are high-bulk, low unit-value, high place-value mineral commodity that are used to provide bulk, strength and wear resistance in construction applications (Robinson *et al.*, 2004). Aggregates are used to improve both the volume stability and durability of the resulting concrete. It is generally viewed that aggregates were completely inert filler in concrete. However, this notion has been found false as in some cases its chemical composition and physical characteristics affected to a certain degree the properties of both plastic and hardened states (Dhir and Jackson, 1996; Tasong *et al.*, 1998). Concrete is made with aggregate particles covering a range of sizes, of which the main division being at a size of 5 mm. This divides the fine aggregates from coarse aggregates ($\geq$ 5 mm) (Neville and Brooks, 1991).

2.1.1 (c) Water

Water is another important ingredient in the manufacturing of concrete. In addition to reacting with cement, and thus causing it to set and harden (hydration process), it also facilitates mixing, placing and compacting of the fresh concrete. It is also used for washing the aggregates and for curing purposes. In general, water used for drinking, such as tap water was acceptable for mixing concrete (Dhir and Jackson, 1996).

2.1.2 Properties of pedestrian block

Pedestrian blocks are recorded to have at least a compressive strength of 20 MPa to 30 MPa based on their functions (Oliver-Solà *et al.*, 2009). Poon and Lam (2008) recorded that the density of the pedestrian blocks were usually range between 2330 kg/m^3 to 2400 kg/m^3. The tensile strength should be around 3.0 MPa to 5.0 MPa. Atici and Ersoy (2008), recently stated that the fracture toughness of pedestrian blocks was important for crack control. The durability of pedestrian blocks was determined by the concrete mixture design and was mainly made from natural aggregates. Limbachiya *et al.* (2007) mentioned that the coarse natural aggregates used were almost pure in SiO_2, while the fine natural aggregates (or sand) show a richer composition in CaO.

2.1.3 Use of pedestrian block

Pedestrian blocks were widely used in flooring and covering applications such as city roads, pedestrian foots, gardening architecture and many surface coverings (Atici and Ersoy, 2008). There were four combinations of functions for the pedestrian block as follows (Oliver-Solà *et al.*, 2009):

1) Pedestrian traffic only

2) Underground services and pedestrian traffic

3) Motorized traffic and pedestrian traffic; and

4) Motorized traffic, underground services and pedestrian traffic

2.1.4 Pedestrian block manufacturing with alternative aggregates

Initially, recycling of construction wastes was first carried out after the Second World War in Germany (Rao *et al.*, 2007). Since then, there were a lot of research works carried out in several countries utilising construction wastes as a constituent in new concrete. Thus, these new aggregates or commonly known as recycled aggregates (RA) could originated from broken concrete, bricks, tiles, glass or broken pavement. Concrete made using such aggregates is referred to as recycled aggregate concrete (RAC). The necessity for the reuse of RA will establish the presuppositions for substantial protection of natural sources of country, which are neither endless nor inexpensive. In addition, there will be a decrease of high volumes of fresh concrete wastes, which illegally ends up in uncontrolled areas of deposition. Finally, the aim of sustainable development will be followed and consequently, the basis for a friendly co-existence of man and nature is set.

2.1.4 (a) Recycled concrete aggregates (RCA)

Concrete rubbles usually constitute the largest proportion of construction and demolition wastes. It has been shown that crushed concrete rubbles, after separation from other construction and demolition wastes and sieved, can be used as a substitute for natural coarse and fine aggregates in concrete. The types of recycled material were called recycled concrete aggregates (RCA) (Poon *et al.*, 2002). The use of RCA is largely a matter of economics, with a number of factors playing a role. Probably the foremost among these is the cost of transportation of both the construction and demolition debris from the demolition site to the nearest suitable landfill and of the virgin aggregate from its source to the construction site. Next, is the cost of land-filling construction and demolition debris, which has a tendency of increasing faster than the rate of inflation, especially in areas of increasingly scarce suitable landfills (Meyer, 2009).

Rao *et al.* (2007) did a review on the properties of RCA. It is accepted that RCA either fine or coarse can be obtained by primary and secondary crushing, and subsequent removal of impurities. Katz (2003) observed that the aggregates prepared from old concretes crushed at various ages exhibited the same size distribution and appeared to have no significant change in the grading of the aggregates despite the difference in the strengths of the concrete that they were made from. The water absorption in RCA ranges from 3 to 12 % for the coarse and the fine fractions with the actual value depending upon the type of concrete used for producing the aggregates. This value was actually much higher than that of the natural aggregates whose absorption was about 0.5-1.0%, because of the high porosity of the RCA attributed by the mortar residues adhered onto the original concrete (Katz, 2003). As a result, it would affect the workability of the fresh concrete. Studies have also shown that such aggregates were also used as sub-basement in flexible pavements, and in rigid pavements. In 2008, Gonzalez-Fonteboa and Martinez-Abella investigated on the shape, grading and physical mechanical properties of RCA. In general, the natural aggregates and RCA showed continuous grading curves, and a similar fineness modulus for equivalent fractions which would have a positive impact on the concrete mixes. The RCA also had an angular with multiple cracking faces but had a lower flakiness index if compared to natural aggregates. It was also found that the density of the RCA was lower compared to conventional natural aggregates. Tam and Tam (2007) concluded that these could be due to the existence of porous and less dense residual mortar lumps or particles adhering to the surface of larger aggregate particles. With those properties, it was found that the workability of RAC for the same water content in the concrete was lower, especially when the replacement level exceeded 50% (Rao *et al.*, 2007). Topcu and Guncan (1995) first reviewed on the properties of RAC and found that the compressive strength and water-cement ratio (W/C) of RAC were lower than the conventional aggregate concrete. If the RCA were of fine aggregates, the RAC manufactured used an increase amount of cement at 34-46 kg per 0.8 m^3 (Gonzalez-Fonteboa and Martinez-Abella, 2008). Sagoe-Crentsil *et al.* (2001) observed that the marginal difference between RAC and normal concrete wet densities attributed could be to the presence of lower-density residual cement mortar that was attached to the aggregate particles. Recently, Poon and Lam (2008) showed that the density of the blocks could be reduced further when the aggregate-cement (A/C) ratio was increased.

In terms of mechanical properties, the manufactured RAC was found to have a reduction in compressive and flexural strengths (Topcu and Guncan, 1995). However, the extent of reduction is related to the parameters such replacement ratio, water/cement ratio and moisture condition of the recycled aggregates (Sagoe-Crentsil *et al.*, 2001; Katz, 2003; Rao *et al.*, 2007). Katz (2003) found that the concrete made from 100% RAC was weaker than concrete made with natural aggregates with the same W/C ratio. Tu *et al.* (2006) also added that the RAC have a 20-30% reduction in compressive strength compared to normal concrete. In fact, most researchers concluded that as the replacement ratio of RCA increased, the compressive strength would decreased (Topcu and Guncan, 1995; Poon *et al.*, 2002; Katz, 2003; Tu *et al.*, 2006; Eguchi *et al.*, 2007; Tam and Tam, 2007; Poon and Lam, 2008). However, when the RAC is made of fine RCA, the compressive strength did not seem to be affected by the fine aggregates replacement ratio, at least up to 30% replacement ratios (Evangelista and Brito, 2007). The ratio for the flexural strength to the compressive strength is in the range of 16-23%. These values were about 10-15% lower compared to the recommendation of certain world standards (Katz, 2003; Rao